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Assessing spatial distribution of heavy metal contamination in groundwater and associated human health risk in the Chittagong industrial area, Bangladesh

Md. Swadhin Hossain [a], Ashfaqur Rahman [b], Elsai Mati Asefa [c,*], Mahfuza Parveen [a], Md. Reaz Uddin [d]

[a] Department of Environmental Science and Disaster Management, Daffodil International University, Dhaka 1216, Bangladesh
[b] Department of Civil Engineering, Chittagong University of Engineering and Technology, Chittagong 4349, Bangladesh
[c] School of Environmental Health, College of Health and Medical Sciences, Haramaya University, Harar 235, Ethiopia
[d] Institute of Water and Flood Management, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

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ABSTRACT

Heavy metal contamination of groundwater presents serious environmental and public health challenges, especially in industrial areas. This study was conducted to address the gap in understanding the health risks of heavy metal exposure in industrial regions, specifically in the Chittagong industrial zone in Bangladesh. A total of 34 groundwater samples were analyzed using indices such as the Heavy Metal Pollution Index (HPI), Heavy Metal Evaluation Index (HEI), and health risk metrics, including Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR). The findings revealed widespread contamination, with 53 % of samples exceeding the HPI threshold, making the water unsuitable for drinking. Key contaminants identified include arsenic (As), chromium (Cr), cadmium (Cd), and lead (Pb), with arsenic posing the most significant risk. The study highlights the underexplored health impacts of these contaminants in the Chittagong industrial region, with arsenic levels significantly contributing to high HQ values, where 82.35 % of children samples and 61.76 % of adults samples exceeded safe limits. The HI further indicated severe non-carcinogenic risks, with 67.65 % of samples for children and 47.06 % for adults surpassing the safe threshold. Carcinogenic risk assessments found that arsenic poses the highest risk for both children and adults, with mean CR values of 2.04×10^{-3} for children and 6.70×10^{-3} for adults, both above the acceptable limit. The spatial distribution maps highlight key hotspots, indicating that the southern region experienced the highest levels of contamination. The present study contributes to address the significant health risks posed by heavy metal contamination, emphasizing the urgent need for mitigation measures in industrial regions to protect vulnerable populations.

1. Introduction

Groundwater is a vital natural resource, providing essential freshwater for domestic, agricultural, and industrial purposes worldwide. In areas where surface water is either unavailable or inadequately treated, groundwater is a crucial source of potable water (Raheja et al., 2024). Groundwater dependencies exist in water-stressed areas worldwide, such as arid zones in Sub-Saharan Africa and rapidly urbanizing parts of Southeast Asia (Aswal et al., 2023; Bouselsal et al., 2025; Omeka et al., 2024). Similarly, In Bangladesh, groundwater plays a crucial role, providing nearly 98 % of drinking water and about 80 % of irrigation water during the dry season (Shamsudduha et al., 2020), with approximately 32 km^3 withdrawn annually, accounting for about 4 % of global groundwater withdrawal (Hanasaki et al., 2018). As a developing country, Bangladesh is undergoing rapid industrialization, with the Chittagong industrial area being one of the largest and most heavily industrialized regions. In this region, around 90 % of the population depends on groundwater for domestic use, while industries account for approximately 45 % of the annual groundwater extraction (DoE, 2021). However, despite its critical role, the sustainability of groundwater resources in industrial areas of Bangladesh faces significant threats. Anthropogenic activities, such as the discharge of untreated industrial

* Corresponding author.
E-mail address: Elsai.mati@haramaya.edu.et (E.M. Asefa).

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effluent, improper hazardous waste disposal, and over-extraction of groundwater, compromise water quality and pose health risks, particularly in industrial zones like Chittagong.

The emergence of hazardous substances, such as heavy metals in groundwater, has become a major environmental concern from a global perspective due to their persistence and toxicity (El Baroudi et al., 2024). Unlike organic pollutants, heavy metals are persistent in nature, as they cannot biodegrade and tend to accumulate within ecosystems, posing considerable threats to the environment and human health (Haque, 2022). Heavy metals like Pb, Cd, As, Cr, and Ni are considered the most hazardous to groundwater systems among such water contaminants (Karthikeyan1 et al., 2021). Industrial effluents and mining operations are primary contamination drivers, as evidenced in Saudi Arabia and Nigerian watersheds (Abba et al., 2024; Egbueri et al., 2025b). Heavy metal contamination often originates in soils, where industrial discharges, mining waste, and agrochemicals accumulate before leaching into groundwater via rainfall or irrigation (Doyi et al., 2018; Xu et al., 2024). As evidenced by arsenic-laden soils in mining areas, exhibiting delayed groundwater contamination due to redox-driven mobilization (Ossai et al., 2020). Soil-groundwater interdependence complicates remediation, as saturated soils act as secondary pollution sources during recharge, with hydraulic conductivity influencing metal retention (Xu et al., 2023; Xu and Yi, 2022). Unlike soil treatments, aquifer remediation is costlier, underscoring the urgency of preemptive studies.

The health implications due to heavy metal contamination are indeed serious and multifaceted. These metals interfere with the critical biological process, mostly leading to irrecoverable damage (Nivetha et al., 2021). Chronic arsenic exposure causes cardiovascular diseases, neuropathy, and developmental delays in children, with cancers documented in Bangladesh (Ahmad and Khan, 2023), Latin America (Khan et al., 2020), and Canada (Saint-Jacques et al., 2018), highlighting its global threat. Lead exposure causes cognitive impairment, behavioral disorders, and neurological deficits in children hypertension, kidney impairment, and reproductive issues in adults (Aralu et al., 2024; Egbueri et al., 2024). Cadmium is another toxic metal that affects renal impairment, softens the bones, and increases the risk of bone fractures due to calcium depletion (Burke et al., 2016). Chromium causes respiratory and gastrointestinal cancers, skin ulcers, and liver toxicity (Georgaki and Charalambous, 2023). Nickel, while an essential trace element, can induce allergic dermatitis; exposure to it in excess is related to the incidences of lung and nasal cancers (Francisco et al., 2019). These biological mechanisms demand a strict monitoring and mitigation strategy concerning heavy metal contamination. Vulnerable populations include children and pregnant women, who have a higher risk for the adverse effects of heavy metals. Children have immature organs and a higher metabolic rate compared with adults; therefore, they are very susceptible to the neurotoxic effects of heavy metals, which may cause long-term cognitive and physical damage (Al osman et al., 2019). Besides, occupational exposure to heavy metals in industrial workers elevates the likelihood of developing persistent diseases like cancer, respiratory disorders, and damage to organs (Briffa et al., 2020).

Heavy metal contamination in groundwater necessitates robust methodological frameworks to assess pollution levels and health risks (Egbueri et al., 2025a). Globally, indices like the Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI) have been widely applied to quantify cumulative contamination, as demonstrated in industrial regions of India and Ghana (Doyi et al., 2018; Sridhar and Parimalarenganayaki, 2024). Similarly, health risk assessments, including Hazard Quotient (HQ), Hazard Index (HI), and Cancer Risk (CR), are critical for evaluating exposure pathways, as validated in transboundary studies (Aralu et al., 2025; Nduka et al., 2023). These methodologies are particularly suited for industrial zones like Chittagong, where multi-metal contamination demands integrated spatial and statistical analysis to identify hotspots and prioritize remediation. Geospatial techniques like Inverse Distance Weighting (IDW) in GIS, applied in regions, enable precise contamination modeling.

The Chittagong industrial area stands as a stark reminder of the environmental costs accompanying unchecked industrial growth, a challenge echoing across rapidly developing regions from Nigeria's agro-industrial basins to India's mining corridors. While earlier studies, such as Hossain et al. (2016), pinpointed lead contamination near shipbreaking yards, and Rahman et al. (2020) traced the majority of chromium, cadmium, and lead samples in the Meghna Ghat industrial area, surpassing Bangladesh drinking water quality standard, these efforts offer only snapshots of a far broader crisis. For instance, Hoque et al. (2024) mapped arsenic hotspots but omitted cancer risk quantification, and Rakib et al. (2022) assessed health impacts without spatial analysis. Such fragmented insights leave policymakers in the dark about cumulative risks. This study pioneers a comprehensive framework integrating multi-metal analysis, geospatial modeling, and health risk assessment that has not been applied in Chittagong region before. The study employs geospatial techniques to correlate contamination hotspots with specific industries, while HQ and CR frameworks quantify health risks for children and adults. The primary aim of this study is to provide a comprehensive assessment of heavy metal contamination, evaluate the associated human health risks using Hazard Quotient (HQ) and Cancer Risk (CR) indices, and conduct spatial risk mapping to identify contamination hotspots. This study provides critical data to safeguard groundwater quality and public health in Chittagong, Bangladesh, offering an adaptable model for industrializing regions globally. It supports SDG 6 (Clean Water) by protecting groundwater and addresses SDG 3 (Good Health) by reducing heavy metal health risks.

2. Methodology

2.1. Study area

The Chittagong industrial area (22.3365° N, 91.8317° E) is located in the southeastern part of Bangladesh with a very high population density (BBS, 2021). Various types of industrial, urban, and coastal landscapes prevail in the study area. This area features a tropical monsoon climate marked by pronounced rainy and arid periods, with annual precipitation often exceeding 2500 mm (BBS, 2023). This heavy rainfall, concentrated between June and September, drives surface runoff that transports contaminants into groundwater systems. The topography includes coastal plains and undulating hilly terrain, with topography contributing to varied water flow and drainage pattern.

Geologically, the region is underlain by clay, silt, and sandstone sedimentary formations (Quaternary alluvial deposits and Tertiary sandstone) underpinning a diverse aquifer system. Shallow aquifers (5–25 m depth) dominate the area, with hydraulic conductivity ranging from 1.5 to 4.0 m/day, facilitating rapid contaminant migration. The recharge of these aquifers occurs through monsoonal precipitation and surface water sourced from adjacent rivers, with the Bay of Bengal contributing to groundwater dynamics through tidal influences and occasional saline intrusion (Zahid et al., 2018). Geomorphologically, the region features coastal floodplains, uplifted terraces, and undulating hills with slopes up to 15°, creating localized zones of rapid infiltration and erosion that mobilize heavy metals (Rakib et al., 2022). Vegetation in the area is characterized by mangrove forests along the coast, which play a role in filtering contaminants, while urban sprawl has led to deforestation and reduced natural filtration. Environmental hygiene is a concern due to industrial discharges and inadequate waste management, which contribute to the accumulation of contaminants in the groundwater and surrounding ecosystems.

2.2. Sample collection and analysis

A total of 34 groundwater samples were collected in June 2024 from tube-wells located in the Chittagong industrial area, employing a

random sampling method (Fig. 1). At each sampling site, the tube well was pumped for 10–15 min to ensure the water sampled accurately reflected the aquifer. Before sampling, each bottle was thoroughly rinsed three times using the groundwater from the respective site to prevent contamination. For each site, two separate 500 mL pre-cleaned polyethylene bottles were filled with groundwater. For trace element analysis, samples were acidified with concentrated HNO_3 (2 ml/L) to maintain a pH below 2, while unacidified samples were preserved for other analysis (APHA, 2017). The collection, handling, and storage of samples strictly complied with the guidelines outlined by the USEPA (2012).

Groundwater samples were analyzed in the Environmental Engineering Laboratory of Chittagong University of Engineering and Technology. The pH, EC, and TDS were analyzed using Hanna Multiparameter pH, TDS, EC, and Temperature Meter (HI9811–51). Heavy metals (Cr, Mn, Fe, Ni, Cu, Zn, As, Cd, Pb) were determined utilizing an atomic spectrophotometer (AAS, Model: AA-7000; Shimadzu, Japan City) with standard methods of APHA (2012). Only high-purity analytical-grade reagents were used to ensure accuracy. To maintain precision, each sample underwent triadic analysis, and after the measurement of every ten samples, the instrument was recalibrated.

2.3. Heavy metal pollution index (HPI)

The HPI serves as a reliable and widely applied method for analyzing groundwater quality through the cumulative assessment of multiple heavy metals (Baskaran and Abraham, 2022). The HPI was calculated using Eq. (1).

$$HPI = \sum_{i=1}^{n} W_i Q_i \sum_{i=1}^{n} W_i \tag{1}$$

In this equation, W_i represents the unit weight of the i th metal, calculated based on its permissible limit, and Q_i is the sub-index of the i th metal, reflecting its relative contribution to pollution. The sub-index Q_i was determined using Eq. (2).

$$Q_i = \sum_{i=1}^{n} |M_i - I_i| S_i - I_i \tag{2}$$

Here, M_i denotes the measured concentration of the metal in the groundwater sample, I_i represents the optimal concentration of a heavy metal in uncontaminated groundwater, as defined by regulatory guidelines. For non-essential toxic metals, I_i is universally recognized as zero to reflect the absence of anthropogenic inputs, while for essential metals I_i aligns with natural background levels. S_i corresponds to the permissible limit. The I_i values were taken from the MAC values of the metals and the S_i values were from the standard values set by BDWS (1997). W_i was computed as $1/S_i$ (Mahammad et al., 2022). Generally, HPI greater than 100 is considered to be the critical limit to drinking water quality (Tiwari et al., 2015). However, a comprehensive classification system proposed by Vetrimurugan et al. (2017) was used in this study, as shown in (Table 3).

2.4. Heavy metal evaluation index (HEI)

The HEI is a crucial parameter used to quantify the contamination level of groundwater by heavy metals. The HEI was calculated using the

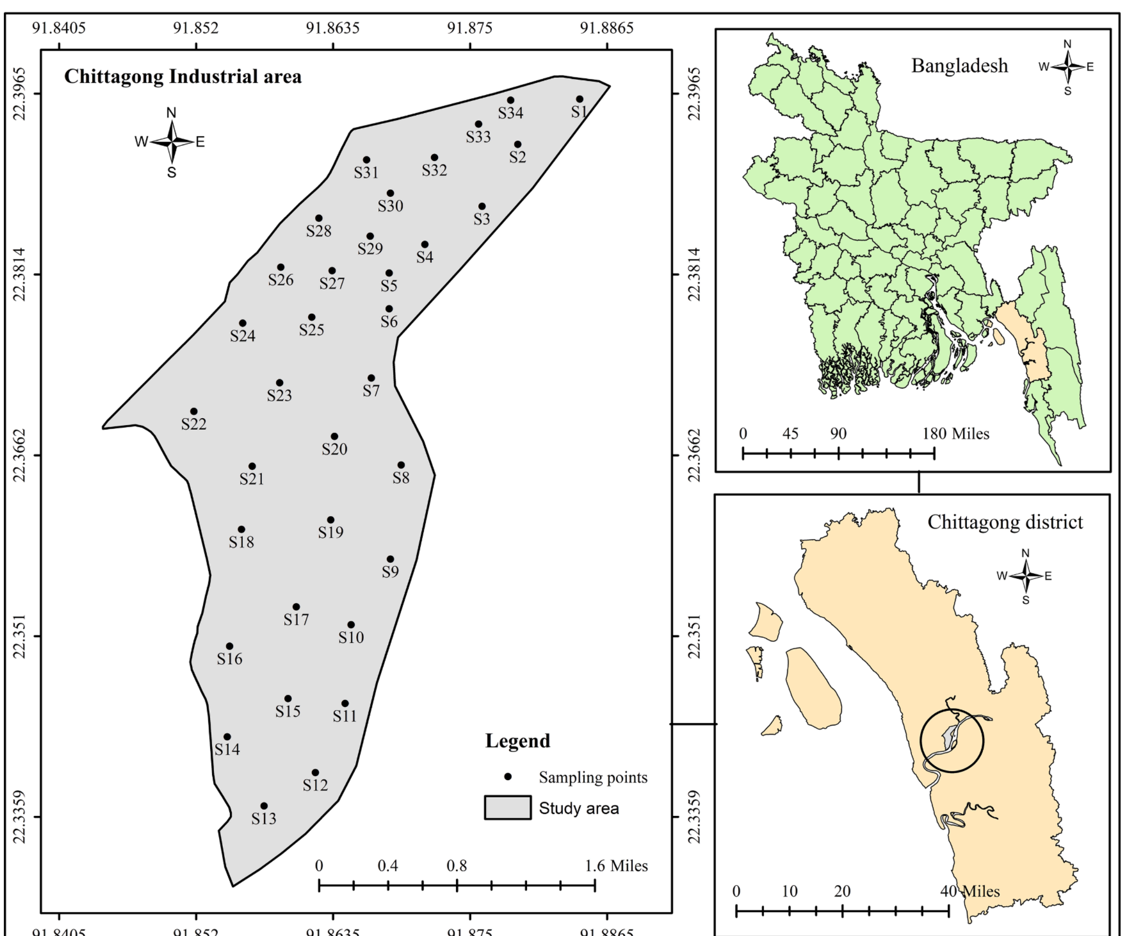

Fig. 1. Study area and sampling locations.

Eq. (3).

$$HEI = \sum_{i=1}^{n} \left(\frac{C_i}{S_i}\right) \quad (3)$$

Where C_i is the measured concentration and S_i is the permissible limit of the i th heavy metal, adopted from the Bangladesh Drinking Water Quality Standards BDWS (1997). Several Recent studies have applied the HEI to assess groundwater contamination by heavy metals (Dheeraj et al., 2024; Nisar et al., 2024). HEI classification system used in this study, as shown in (Table 3).

2.5. Human health risk assessment

The assessment of human health risks examines the possible dangers to human health that may result from exposure to hazardous substances, particularly heavy metals. This procedure evaluates the probability of negative impacts on individuals resulting from their exposure to harmful substances (Chowdhury et al., 2025). This investigation employed the health risk assessment framework proposed by the USEPA (2011) To analyze possible health hazards for both adults and children in the research area via the ingestion pathway.

2.6. Estimation of CDI of heavy metals

The chronic daily intake (CDI) of heavy metals was estimated to quantify the amount of metal exposure through ingestion and dermal contact with groundwater (Yang et al., 2012). The calculation of the CDI for Cr, Mn, Fe, Ni, Cu, Zn, As, Cd, and Pb via groundwater consumption was conducted for the study area utilizing Eq. (4).

$$\mathrm{CDI} = \frac{\mathrm{C} \times \mathrm{IR} \times \mathrm{EF} \times \mathrm{ED}}{\mathrm{AT} \times \mathrm{BW}} \quad (4)$$

In this equation, C is the concentration of the heavy metal in groundwater (mg/L), IR is the daily water ingestion rate (2.0 L/day for adults and 1.0 L/day for children, respectively) (John et al., 2024; Sridhar and Parimalarenganayaki, 2024; USEPA, 1989), EF is the exposure frequency (365 days per year), and ED is the exposure duration (70 years for adults and 10 years for children) (Shaibur et al., 2024). BW represents body weight (70 kg for adults and 15 kg for children) (Rahman et al., 2018), and AT is the average life expectancy. The study calibrates IR, ED, and the BW for the local population based on regional data.

2.6.1. Estimation of HQ and HI of heavy metals

The Hazard Quotient (HQ) is a useful metric for evaluating potential non-carcinogenic health hazards linked to exposure to pollutants, such as heavy metals (Rakib et al., 2022). The HQ is calculated by Eq. (5).

$$\mathrm{HQ} = \frac{\mathrm{CDI}}{\mathrm{RfD}} \quad (5)$$

Where RfD refers to the oral reference dose for heavy metals presented in (Table 4). The Hazard Index (HI) is used to assess the cumulative non-carcinogenic health risks posed by multiple contaminants. It is calculated as the sum of the Hazard Quotients (HQs) for all analyzed substances, using Eq. (6).

$$\mathrm{HI} = \sum \mathrm{HQ} \quad (6)$$

An HQ or HI value below 1 indicates safe exposure levels, while a value of 1 or higher suggests potential risks, with HI reflecting the combined impact of multiple contaminants (Qu et al., 2022).

2.6.2. Estimation of CR of heavy metals

The Cancer Risk (CR) assesses the likelihood of an individual developing cancer over their lifetime as a result of exposure to carcinogenic substances (Rahman et al., 2018). Eq. (7) was utilized to calculate CR via the oral exposure pathway.

$$\mathrm{CR} = \mathrm{CDI} \times \mathrm{CSF} \quad (7)$$

Here, CR denotes carcinogenic risk through the oral pathway, while CSF refers to the cancer slope factor, which measures a substance's carcinogenic potential. The CSF values for each toxic metal analyzed in this study are provided in (Table 6). The CR value below 1×10^{-6} is generally considered negligible or very low and can often be disregarded. In contrast, a cancer risk above 1×10^{-4} is unacceptable. Risks within the range of 1×10^{-6} to 1×10^{-4} are typically viewed as acceptable or tolerable under most regulatory standards (Sajjadi et al., 2022). The cumulative contribution of the four analyzed metals was calculated and presented as the total cancer risk (CRt), as expressed in Eq. (8).

$$\text{Total carcinogenic risk(CRt)} = \sum \mathrm{CR} \quad (8)$$

The detailed framework for assessing carcinogenic risk is presented in (Table 6).

2.7. Statistical and geospatial analysis

The data analysis for this study employed descriptive statistical methods to provide a comprehensive understanding of the variables. Pearson correlation analysis was conducted to evaluate the relationships between variables, with all computations performed using SPSS 22 software. The Inverse Distance Weighting (IDW) interpolation technique was applied to examine the spatial variability of groundwater parameters. This analysis was implemented using ArcGIS 10.8.2, enabling the visualization and assessment of spatial patterns within the dataset.

3. Result and discussion

3.1. Heavy metals concentration in the groundwater sample

Table 1 presents the concentration levels of heavy metals and physicochemical parameters in the groundwater samples. The findings reveal substantial variation in contamination, with several samples exceeding the permissible limits.

The pH values ranged between 6.58 and 7.92, falling within the WHO and BDWS recommended range of 6.5–8.5, indicating that the water is generally neutral to slightly alkaline. However, variations in pH may reflect localized influences from industrial discharges or geochemical interactions (Saha and Paul, 2019). The EC values, ranging from 585 μS/cm to 4589 μS/cm, were significantly higher than typical levels in natural groundwater, indicating substantial ionic content, likely resulting from industrial effluents. Similarly, TDS concentrations ranged from 380 mg/L to 2980 mg/L, with 64.71 % of samples exceeding the BDWS guideline. High levels of TDS indicate that salts and minerals have dissolved and could also be contaminated by anthropogenic activities (Xiao et al., 2021).

The Chromium concentration ranged from 0.00 to 0.195 mg/L, and 43 % of the samples exceeded the WHO and BDWS permissible limit. Chromium contamination may be due to industrial processes such as metal plating, tanning, and chemical production in Chittagong. Manganese concentration ranged from 0.00 to 0.384 mg/L, and 56 % of the samples exceeded the BDWS guideline. While manganese is a vital micronutrient, excessive intake has been associated with harmful effects on the nervous system (Sharma et al., 2021). The Iron concentrations were the highest among the analyzed metals, reaching up to 8.56 mg/L, with 71 % of the samples exceeding the BDWS limit of 1.0 mg/L. High iron concentrations in groundwater are typically associated with the weathering of iron-bearing minerals and the release of industrial effluents. Although iron is not directly toxic, its excessive presence affects the aesthetic quality of water and poses health risks, such as hemosiderosis from chronic exposure, which can lead to liver, pancreatic, and cardiac

Table 1
Concentration of physicochemical parameters and heavy metals in the study region (Units: EC in μS/cm, TDS in ppm, and heavy metals in mg/L).

Sample Id	pH	EC	TDS	Cr	Mn	Fe	Ni	Cu	Zn	As	Cd	Pb
S1	7.76	4589	2980	0.123	0.234	8.35	0.06	0.24	0.56	0.051	0.012	0.078
S2	7.62	4420	2870	0.106	0.341	7.65	0.072	0.22	0.51	0.055	0.011	0.081
S3	7.89	3604	2340	0.115	0.336	5.87	0.065	0.19	0.61	0.102	0.013	0.08
S4	7.92	4143	2690	0.145	0.312	5.76	0.068	0.23	0.76	0.026	0.014	0.078
S5	7.62	3835	2490	0.129	0.368	6.10	0.052	0.18	0.81	0.029	0.011	0.083
S6	7.88	4250	2760	0.045	0.123	5.34	0.046	0.22	0.77	0.031	0.008	0.085
S7	7.54	1910	1270	0.048	0.145	6.45	0.050	0.49	1.12	0.027	0.006	0.088
S8	7.48	2171	1410	0.042	0.107	5.07	0.056	0.47	1.34	0.028	0.005	0.096
S9	7.51	2064	1340	0.045	0.112	6.56	0.046	0.48	1.06	0.030	0.006	0.078
S10	7.56	2710	1760	0.137	0.125	6.98	0.039	0.45	0.77	0.018	0.006	0.092
S11	7.72	4281	2780	0.122	0.374	7.87	0.107	0.73	0.52	0.015	0.019	0.090
S12	7.85	4235	2750	0.187	0.384	8.56	0.068	0.69	0.53	0.018	0.012	0.081
S13	7.82	3850	2500	0.195	0.319	6.45	0.059	0.74	0.45	0.020	0.014	0.105
S14	7.64	3835	2490	0.172	0.368	7.54	0.112	1.02	0.47	0.018	0.011	0.112
S15	7.45	2864	1860	0.024	0.216	6.90	0.056	0.46	0.42	0.009	0.013	0.065
S16	7.39	2695	1750	0.021	0.243	3.05	0.061	0.48	0.48	0.007	0.014	0.062
S17	7.23	2710	1760	0.018	0.085	2.87	0.053	0.45	0.24	0.012	0.012	0.056
S18	7.36	2541	1650	0.015	0.078	2.12	0.048	0.21	0.34	0.006	0.006	0.052
S19	7.48	2310	1500	0.017	0.080	3.24	0.042	0.22	0.38	0.012	0.007	0.024
S20	7.50	2264	1470	0.00	0.082	3.42	0.019	0.18	0.42	0.00	0.00	0.018
S21	7.19	1509	980	0.00	0.068	4.98	0.024	0.023	0.47	0.00	0.00	0.008
S22	7.32	1401	910	0.024	0.034	2.15	0.018	0.14	0.36	0.00	0.004	0.006
S23	6.84	970	630	0.016	0.031	0.75	0.005	0.15	0.35	0.005	0.005	0.012
S24	6.86	1093	710	0.022	0.026	0.92	0.004	0.20	0.43	0.006	0.006	0.007
S25	6.78	785	510	0.001	0.038	0.89	0.012	0.18	0.21	0.002	0.00	0.00
S26	6.58	693	450	0.002	0.018	0.18	0.016	0.17	0.24	0.004	0.00	0.00
S27	7.24	631	410	0.004	0.00	0.22	0.022	0.22	0.12	0.007	0.004	0.009
S28	7.20	755	490	0.00	0.028	0.24	0.015	0.18	0.18	0.00	0.003	0.006
S29	7.08	585	380	0.021	0.032	1.58	0.018	0.12	0.24	0.008	0.004	0.008
S30	7.14	724	470	0.024	0.022	1.98	0.022	0.13	0.28	0.011	0.003	0.00
S31	7.32	708	460	0.021	0.023	2.45	0.028	0.10	0.35	0.013	0.005	0.008
S32	7.65	1093	710	0.027	0.034	2.42	0.026	0.13	0.46	0.015	0.005	0.005
S33	7.46	1725	1120	0.032	0.039	2.31	0.032	0.17	0.34	0.057	0.004	0.028
S34	7.48	1617	1050	0.028	0.032	2.15	0.027	0.14	0.32	0.052	0.004	0.027
MIN	6.58	585.2	380	0.00	0.00	0.18	0.004	0.023	0.12	0.00	0.00	0.00
MAX	7.92	4589.2	2980	0.195	0.384	8.56	0.112	1.02	1.34	0.102	0.019	0.112
MEAN	7.42	2340.35	1520.59	0.0567	0.1429	4.0991	0.0426	0.3060	0.4974	0.0204	0.0073	0.0479
(WHO, 2011)	6.5–8.5	–	500	0.05	0.1	0.3	0.07	2.0	3.0	0.01	0.003	0.01
(BDWS, 1997)	6.5–8.5	–	1000	0.05	0.1	1.0	0.1	1.0	5.0	0.05	0.005	0.05

damage (Teschke, 2024).

The Arsenic concentrations surpassed the WHO (2011) threshold in 47 % of the samples, indicating notable contamination risks. Lead levels in groundwater reached up to 0.112 mg/L, with 18 % of the samples exceeding the limits established by WHO and BDWS. Lead contamination likely originates from industrial emissions, old plumbing systems, and waste disposal practices in the industrial zone. The Cadmium levels were generally within safe limits, though 12 % of the samples exceeded the WHO guideline. Cadmium contamination is often linked to industrial discharges, including those from battery manufacturing and electroplating facilities (Alsubih et al., 2021). The Zinc concentrations ranged from 0.12 mg/L to 1.34 mg/L, with all samples falling within the permissible WHO (2011) guideline. The relatively low levels of zinc in the samples indicate limited anthropogenic contributions compared to other metals. The higher permissible limits for Fe, Ni, Cu, Zn, As, Cd, and Pb in BDWS (1997) compared to WHO (2011) provide distinct risk profiles. However, their combined analysis enables policymakers to align national standards with global health objectives while considering regional contexts. A significant proportion of groundwater samples from the Chittagong industrial area exceeded permissible drinking water standards, underscoring the urgent need for intervention to address contamination.

Table 2 presents a comprehensive analysis of metal concentrations across various industrial regions. In Bangladesh's Chittagong industrial area, several heavy metals, including arsenic, cadmium, lead, iron, and manganese, exceed WHO guidelines. The main cause of this contamination is the shipbreaking and textile industries. In contrast, Karachi's industrial zones in Pakistan are severely polluted with chromium and cadmium due to the tannery industry. Tamil Nadu, India, faces extreme lead contamination from unregulated battery recycling practices. Lagos, Nigeria, and Bagerhat, Bangladesh, also report high levels of iron and cadmium, respectively. What makes Chittagong stand out is its unique combination of arsenic and cadmium contamination, which is less common in other industrial zones. These regional differences highlight

Table 2
Comparative assessment of mean heavy metal concentration in groundwater with previous studies (Unit: mg/L).

Area	Cr	Mn	Fe	Ni	Cu	Zn	As	Cd	Pb	Reference
Lagos, Nigeria	0.0321	0.0082	0.3468	0.0389	0.5464	0.7185	–	0.0005	0.0017	(Ukah et al., 2019)
Tamil Nadu, India	0.048	0.152	0.59	0.216	0.017	0.304	–	–	1.224	(Karthikeyan1 et al., 2021)
Karachi, Pakistan	1.22	0.082	0.738	0.131	–	0.111	–	0.080	0.149	(Murtaza and Usman, 2022)
Bagerhat, Bangladesh	0.2454	0.0050	0.0025	0.0082	0.0080	0.0003		0.0038	0	(Khan and Paul, 2023)
Chittagong, Bangladesh	0.0567	0.1429	4.0991	0.0426	0.306	0.4974	0.0204	0.0073	0.0479	This study

the need for targeted, region-specific policies to address the most common pollutants and better protect groundwater quality and public health in industrial zones worldwide.

The spatial distribution maps of heavy metals in groundwater across the Chittagong industrial area (Fig. 2) demonstrate significant spatial variability, reflecting the combined effects of natural processes and anthropogenic activities. Chromium concentrations (Fig. 2a) are predominantly elevated in the southern and central regions, likely due to industrial discharges such as those from metal plating operations, a trend observed in other industrial zones globally (Tokatli, 2021). Manganese and iron concentrations (Figs. 2b and 2c) are particularly high in the southern zones, suggesting contributions from both geochemical weathering of Mn and Fe-rich minerals and industrial effluent inputs. These results align with research emphasizing the contribution of industrial processes to the concentration of heavy metals in specific areas (Boum-Nkot et al., 2023). Nickel and Copper (Figs. 2d and 2e) show a scattered distribution with notable hotspots near industrial zones, indicating contamination from sources such as electroplating and waste

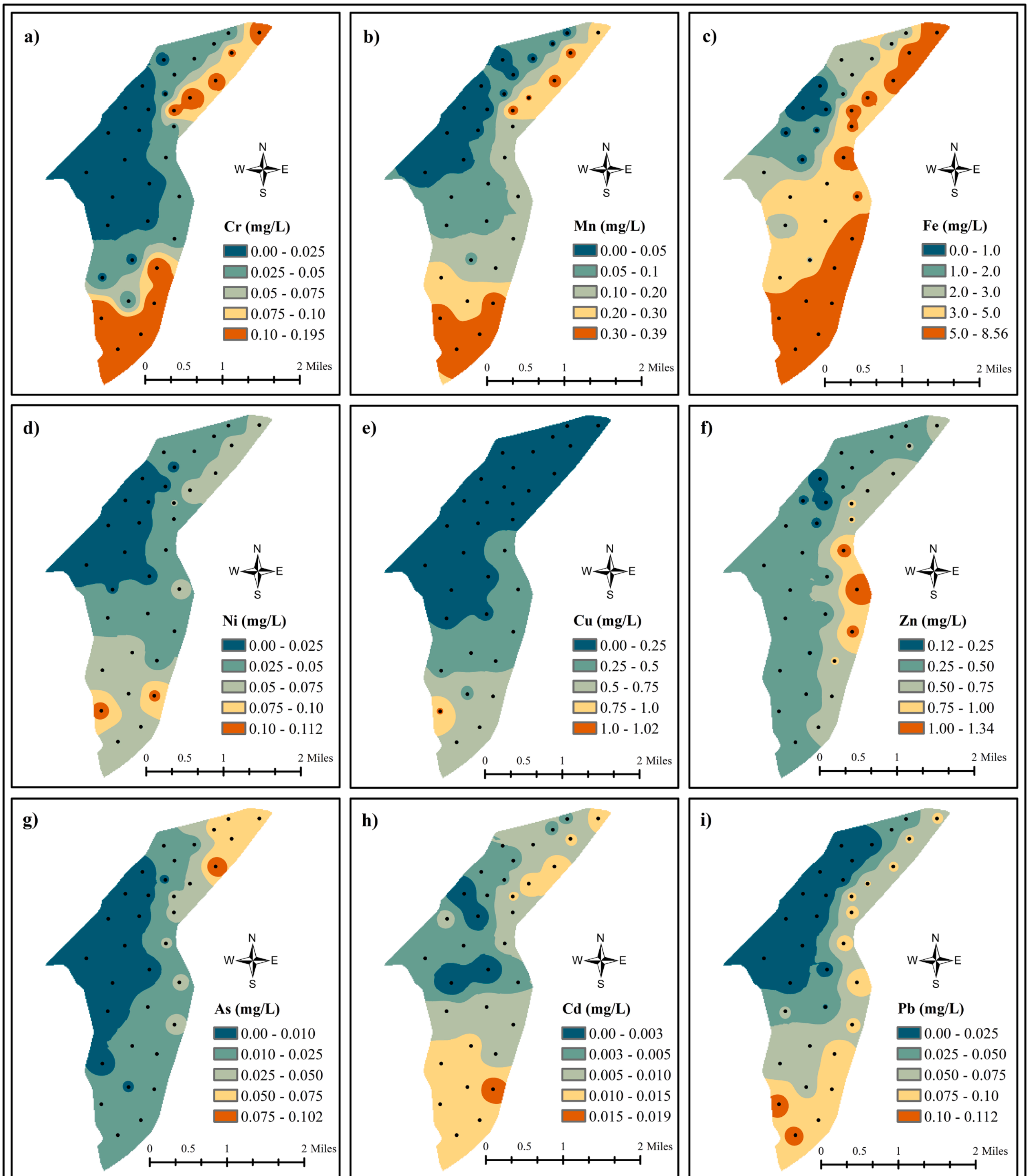

Fig. 2. Spital distribution of a) Cr, b) Mn, c) Fe, d) Ni, e) Cu, f) Zn, g) As, h) Cd, and i) Pb.

disposal. Zn (Fig. 2f) and As (Fig. 2g) exhibit relatively moderate spatial variation, with higher arsenic levels in the northern areas. Cd and Pb (Fig. 2h and 2i) show distinct hotspots near industrial discharge points, highlighting contamination from activities such as battery manufacturing and improper waste handling. The overall distribution patterns reveal a southward increase in contamination, closely correlating with the density of industrial activities. These findings emphasize the need for focused remediation strategies in heavily contaminated areas to manage groundwater pollution effectively, ensuring compliance with safe drinking water standards and protecting public health.

3.2. Correlation analysis of heavy metals in groundwater

The correlation analysis of heavy metals in groundwater, as presented in (Fig. 3), reveals significant interrelations among various physicochemical parameters and heavy metal concentrations.

The EC and TDS exhibit strong positive correlations with key metals such as Fe ($r = 0.85$), Mn ($r = 0.88$), and Pb ($r = 0.85$), indicating that these parameters are highly influenced by the ionic composition of dissolved metals in the groundwater (Islam, 2023). Cr shows strong correlations with Mn ($r = 0.86$), Fe ($r = 0.78$), and Pb ($r = 0.74$), suggesting that these metals share similar geochemical pathways. The significant relationship between Mn and Fe ($r = 0.82$) further underscores their coupled behavior. Moderate correlations between Zn and Cu ($r = 0.76$) indicate their similar geochemical pathways, likely influenced by their complexation behavior and interactions with organic ligands or mineral surfaces (Mostafa et al., 2017). Cd exhibits significant positive correlations with Pb ($r = 0.85$), Fe ($r = 0.82$), and Mn ($r = 0.81$), indicating a tendency for co-occurrence, possibly due to shared environmental matrices such as sediments or colloidal particles. Arsenic exhibits weaker correlations with most metals, including Fe ($r = 0.41$) and Mn ($r = 0.35$), indicating distinct geochemical behavior and mobility pathways. The weak correlations between arsenic and Fe, Mn may reflect different redox-driven release mechanisms. Arsenic mobilization occurs under reducing conditions, dissolving Fe and Mn oxides and releasing adsorbed arsenic. Fe and Mn solubility is directly controlled by redox state fluctuations (Rakhimbekova et al., 2021).

3.3. Heavy metal pollution level of groundwater

The heavy metal pollution levels in groundwater were assessed using the HPI and HEI, as summarized in (Table 2), to evaluate cumulative heavy metal impacts on water quality.

The HPI values varied widely across the samples, ranging from 15.6 to 126.3, revealing significant variability in heavy metal pollution. A substantial proportion (52.94 %) of the samples exhibited HPI values exceeding 100, indicating severe contamination that renders the groundwater “unsuitable” for drinking purposes. This contamination level is markedly higher than the 25 % critical threshold reported in Ojoto Province, Nigeria, where Pb was the dominant pollutant (Egbueri and Mgbenu, 2020). These high values signify substantial cumulative concentrations of metals such as Fe, Mn, Pb, and Cr, which pose serious health risks. Additionally, 50.59 % of the samples showed HPI values between 76 and 100, reflecting “very poor” water quality with significant heavy metal pollution. A smaller fraction of samples (11.76 %) exhibited HPI values between 51 and 75, indicating “poor” water quality that requires attention. In contrast, only 11.76 % of the samples demonstrated HPI values below 25, suggesting “excellent” water quality with minimal heavy metal contamination. These findings underscore the urgent need for stringent regulation of industrial discharges to mitigate Fe, Mn, Pb, and Cr contamination, ensuring safe drinking water in the region.

The HEI values provided an alternative perspective, ranging from 4.2 to 24.8, emphasizing cumulative heavy metal pollution. A majority (52.94 %) of the samples were classified as having “low contamination” levels, with HEI values below 10, reflecting limited cumulative impact from heavy metals like Cd, Pb, and As. These samples represent areas where the cumulative concentration of heavy metals remains within acceptable thresholds for drinking water safety. However, 35.29 % of the samples were categorized as “moderately contaminated,” exhibiting HEI values ranging from 10 to 20, indicating potential risks over prolonged exposure (Aswal et al., 2024). The remaining 11.76 % of the samples recorded HEI values above 20, and exhibited “high contamination”. This moderate-to-high contamination (47.05 % combined) contrasts with industrialized regions of Tripura, northeast India, where over 60 % of groundwater samples exhibited HEI >10 due to intense manufacturing activities (Karmakar et al., 2023), underscoring the

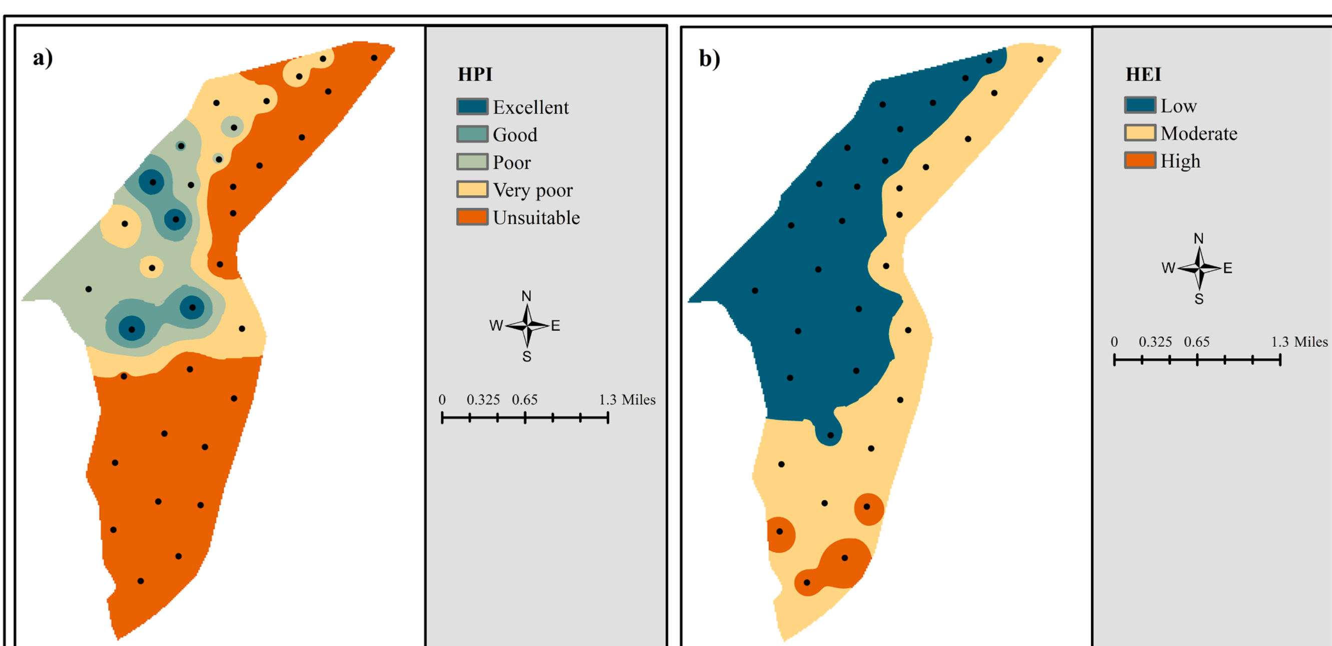

Fig. 3. Correlation heatmap of heavy metals and physicochemical parameters in groundwater samples.

urgency of targeted remediation and stricter industrial discharge controls in this study area.

The spatial distribution maps of the HPI and HEI (Fig 4) provide a visual representation of heavy metal contamination across the Chittagong industrial area. The HPI map (Fig. 4a) reveals a pronounced southward gradient of severe pollution, with a substantial portion of the southern region classified as unsuitable due to elevated heavy metal concentrations. In contrast, the northern zones display better water quality, with scattered areas falling into the excellent or good categories. The HEI map (Fig. 4b) similarly highlights high contamination levels in the southern regions, where several sites are categorized as high, reflecting significant cumulative heavy metal burdens. The northern and central regions are predominantly classified as low or moderate, suggesting comparatively lesser contamination.

3.4. Human health risk assessments

3.4.1. Evaluation of noncarcinogenic health risk

The non-carcinogenic health risks associated with heavy metal contamination were assessed using the HQ and HI through the ingestion pathway.

The HQ values, as presented in (Table 3), provide a detailed assessment of individual metal risks for both children and adults via ingestion pathway. Among children, arsenic exhibited the highest risk, with HQ values ranging from 0.00 to 22.67 and a mean of 4.54, where 82.35 % of the samples exceeded HQ>1, indicating critical health concerns. While this study quantified risks through ingestion, unassessed dermal contact pathways may have contributed to elevated cumulative exposure. Previous research has demonstrated that ingestion was the dominant exposure pathway (Habib et al., 2020). Additionally, previous study that have identified arsenic as a major contaminant in industrialized areas, often associated with negative health outcomes, including developmental delays and immune system impairments in children (Monteiro De Oliveira et al., 2021). Similarly, lead exhibited HQ values between 0.00 and 5.33, with a mean of 2.28 and 61.76 % of samples exceeding HQ>1, signifying a high risk of neurotoxic effects, particularly affecting cognitive and behavioral development in children (Rezaei et al., 2019). Chromium and cadmium, with HQ values exceeding 1 in 32.35 % and 38.24 % of the samples, respectively, further indicate moderate to high risks. High HQ values of these metals indicate vulnerability for children because of their higher intake rates relative to body weight and sensitivity in development to toxic exposure. In contrast, HQs <1 can be observed for Mn, Fe, Ni, Cu, and Zn, with no considerable noncarcinogenic risks detected. These results show that while the essential trace metals, like Mn and Zn, are within safe limits, toxic metals such As, Pb, Cr, and Cd pose serious risks to children's health and require serious intervention.

For adults, the HQ analysis indicates relatively lower risks, yet arsenic and lead remain prominent contaminants of concern. Arsenic displayed HQ values ranging from 0.00 to 9.71, with a mean value of 1.94, and 61.76 % of the samples exceeding HQ>1. This highlights its significant contribution to potential health effects such as cardiovascular diseases, dermal lesions, and gastrointestinal disorders in adults, consistent with previous findings in arsenic-contaminated regions (Riaz et al., 2022). Lead, with HQ values between 0.00 and 2.29 and a mean of 0.98, exceeded HQ>1 in 52.94 % of the samples, emphasizing its continued threat to adult health, particularly in terms of chronic kidney

Table 3
Classification of water quality based on HPI and HEI indices (Dheeraj et al., 2024; Kana, 2022).

Index	Range	Classification	Number of Samples	Percentage of samples	Sample Ids
HPI	<25	Excellent	4	11.76	S20, S21, S25, S26
	26–50	Good	1	2.94	S28
	51–75	Poor	4	11.76	S22, S27, S29, S30
	76–100	Very poor	7	50.59	S8, S23, S24, S31-S34
	>100	Unsuitable	18	52.94	S1-S7, S9-S19
HEI	<10	Low	18	52.94	S17-S34
	10–20	Moderate	12	35.29	S1-S10, S15, S16
	>20	High	4	11.76	S11-S14

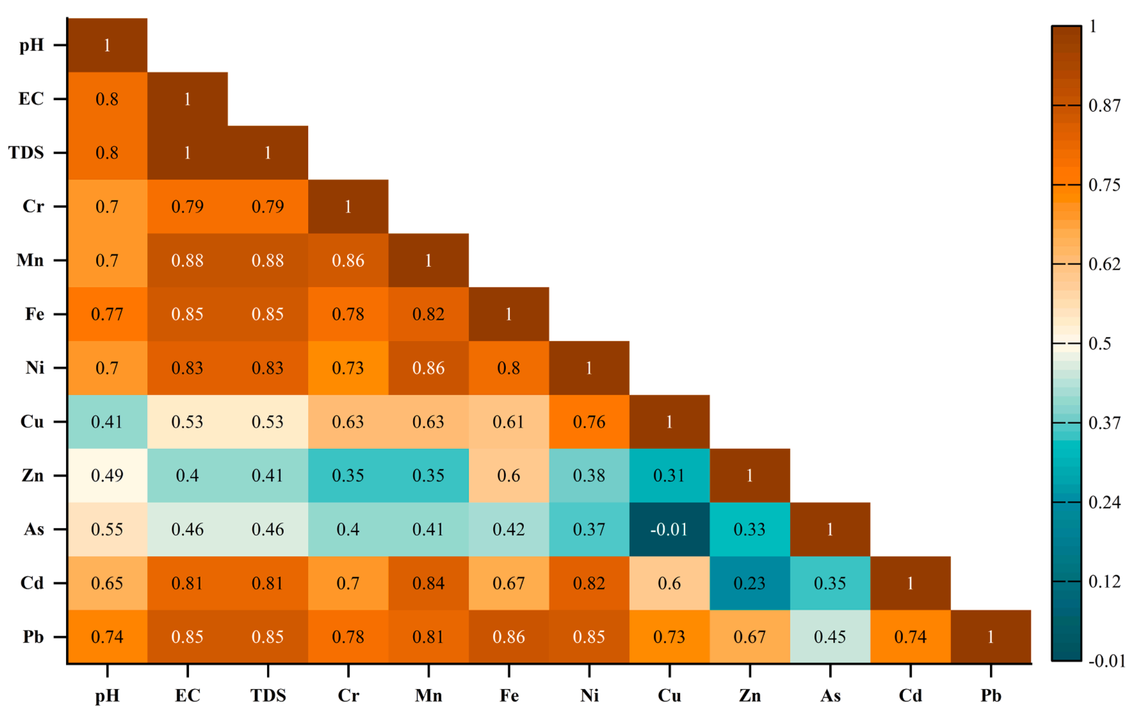

Fig. 4. Spital distribution of a) HPI, and b) HEI.

damage and hypertension (Raj and Das, 2023). Notably, while lead (Pb) and cadmium (Cd) dominated health risks in shallow groundwater of Onitsha, Nigeria (Egbueri, 2020), the study of the Chittagong industrial area in Bangladesh revealed arsenic (As) and cadmium (Cd) to be the primary contaminants of concern. This contrast reflects region specific profiles from local anthropogenic or geogenic sources. Chromium presented HQ values exceeding 1 in 29.41 % of the samples, while cadmium posed a comparatively lower risk, with HQ>1 in only 2.94 % of the samples. Other metals, including Mn, Fe, Ni, Cu, and Zn, showed HQ values below 1, Suggesting minimal health risks for adults. The consistent exceedance of HQ>1 for arsenic and lead necessitates proactive mitigation strategies to address their long-term health impacts.

The chronic health risks for children and adults were evaluated using HI values, as shown in the (Table 4). For children, 67.65 % of the samples exhibited a high risk of chronic health effects due to prolonged exposure to heavy metals. This highlights significant health vulnerabilities in children, particularly from contaminants like arsenic and lead, which are known for their cumulative toxicity. Additionally, 29.41 % of the samples fell into the moderate risk category, suggesting potential health impacts that require close monitoring and intervention (Ogarekpe et al., 2023). Only 2.94 % of samples fell into the low-risk category, and no samples showed negligible risk, emphasizing the overall severity of risks for children.

For adults, the risk distribution was less severe but still concerning. A significant proportion (47.06 %) of the samples showed high chronic health risks. Additionally, 35.29 % of the samples fell into the moderate risk category, highlighting substantial exposure levels to heavy metals over time. In comparison, 17.65 % of the samples were categorized as low risk, while no samples exhibited negligible risk. In comparison to the previous study, which found that groundwater noncarcinogenic health risks were for 43 % of children and 26 % of adults in South Africa (Mthembu et al., 2022), the present study of the Chittagong industrial area in Bangladesh reveals even more severe risks, primarily driven by arsenic and cadmium contamination. These findings demonstrate that, while the risk is relatively lower for adults than for children due to differences in body weight and intake rates, significant long-term exposure to contaminants like arsenic and lead still poses substantial health threats. Such results align with previous studies in industrial regions, emphasizing the importance of targeted mitigation strategies to address chronic risks across different population groups (Vig et al., 2023).

Fig. 5 illustrates the spatial distribution of HI for children and adults across the study area. The map for children (Fig. 5a) highlights widespread high-risk zones in the southern and central regions, with smaller moderate-risk areas toward the north. For adults (Fig. 5b), the distribution shows similar patterns, but with more localized low and moderate risk zones in the northern region. The maps emphasize the spatial variability of chronic health risks, with children facing more extensive high-risk exposure compared to adults.

3.4.2. Evaluation of carcinogenic health risk

High concentrations of heavy metals in groundwater pose a significant threat to human health, particularly through prolonged ingestion exposure (Ayejoto and Egbueri, 2024). The carcinogenic health risks for children, as outlined in (Table 5), indicate that As, Cr, and Cd are the primary contributors.

For children, arsenic is the most critical contaminant, with a mean CR value of 2.04×10^{-3}, followed by cadmium and chromium, with mean CR values of 2.95×10^{-3} and 1.89×10^{-3}, respectively. Lead posed the least risk, with a mean CR of 2.71×10^{-5}. The total carcinogenic risk (CRt) for children reached a mean of 6.91×10^{-3}, significantly exceeding the acceptable threshold of 1×10^{-4} established by the USEPA (2001), indicating substantial risks from heavy metal exposure. From Table 6, it can be observed that 85.29 % of the samples exceeded the acceptable threshold for children. A previous study conducted by Habib et al. (2020) in the Barapukuria coal basin, Bangladesh, found that 57.57 % of the samples showed cancer risk for children. In contrast, the present study conducted in the Chittagong industrial area reveals an even higher cancer risk. These results highlight the elevated vulnerability of children to carcinogenic risks from arsenic, cadmium, and chromium exposure, aligning with multiple research that identifies these metals as major contributors to groundwater contamination-related cancer risks (Singh et al., 2023; Tong et al., 2021). For adults, the risk profile follows a similar trend, with arsenic presenting the highest risk (mean CR: 6.70×10^{-4}), followed by cadmium (1.17×10^{-3}) and chromium (7.05×10^{-4}), while lead remains the least concerning (9.03×10^{-6}). The mean CRt for adults (2.47×10^{-3}) exceeded acceptable limits, with 76.47 % of samples surpassing risk thresholds. This finding closely parallels Vinnarasi et al. (2022) report of 69.75 % exceedance in Tamil Nadu, India, highlighting consistent trans-regional cancer risks in industrialized zones. This research identifies arsenic, cadmium and chromium as the primary contributors to carcinogenic risks in the Chittagong industrial region. These findings emphasize the urgent need for effective remediation strategies to safeguard public health from chronic exposure to contaminated groundwater.

3.5. Implications, limitations, challenges, and future perspectives

This study highlights significant groundwater contamination in the Chittagong industrial area, raising important concerns about water security and sustainable development. With over 80 % of the local population dependent on groundwater, the presence of heavy metals poses a serious threat to water safety. This contamination directly hinders progress towards Sustainable Development Goal (SDG) 6 (access to clean water) and SDG 3 (public health). While the study offers valuable insights, it is important to recognize its limitations. The reliance on a single sampling event in June 2024 restricts our understanding of seasonal variations in heavy metal levels, which could change due to monsoon dilution or varying industrial activities. Additionally, focusing exclusively on ingestion as an exposure pathway may overlook dermal exposure, potentially underestimating cumulative health impacts, especially for industrial workers.

Addressing these issues presents systemic challenges, including weak regulatory enforcement, funding gaps for advanced treatment

Table 4
The HQ value for adult and child through ingestion pathway (Adeyemi and Ojekunle, 2021; USEPA, 2011).

Heavy metal	Hazard quotient (Child)				Hazard quotient (Adult)				Rfd (mg Kg^{-1} day^{-1})
	Min	Max	Mean	HQ>1 sample (%)	Min	Max	Mean	HQ>1 sample (%)	
Cr	0.00	4.33	1.26	32.35	0.00	1.86	0.54	29.41	0.003
Mn	0.00	0.18	0.07	0.00	0.00	0.08	0.03	0.00	0.14
Fe	0.20	0.82	0.39	0.00	0.01	0.35	0.17	0.00	0.7
Ni	0.01	0.37	0.14	0.00	0.01	0.16	0.06	0.00	0.02
Cu	0.04	1.70	0.51	5.88	0.02	0.73	0.22	0.00	0.04
Zn	0.03	0.30	0.11	0.00	0.01	0.13	0.05	0.00	0.3
As	0.00	22.67	4.54	82.35	0.00	9.71	1.94	61.76	0.0003
Cd	0.00	2.53	0.97	38.24	0.00	1.09	0.42	2.94	0.0005
Pb	0.00	5.33	2.28	61.76	0.00	2.29	0.98	52.94	0.0014

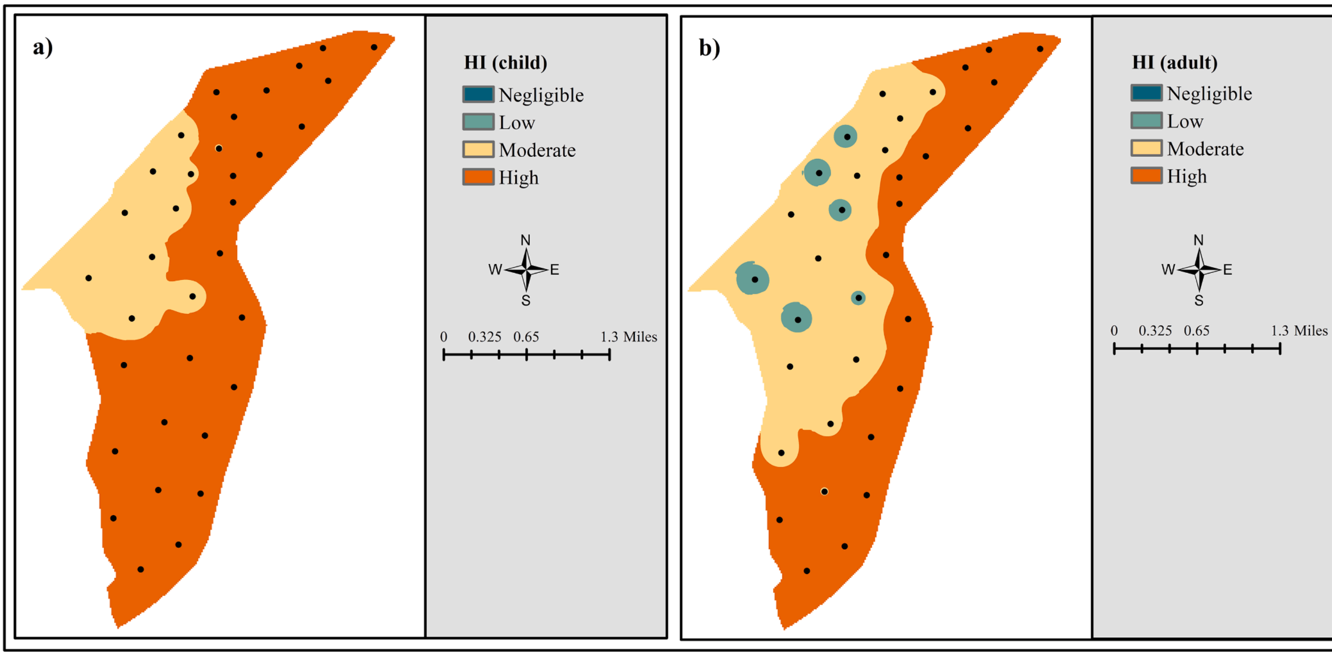

Fig. 5. Spital distribution of a) HI (child), and b) HI (adult).

Table 5
The HI ranges and corresponding chronic risk levels with sample percentages (USEPA, 1989).

Risk level	HI value	Chronic Risk	% of sample (Child)	% of sample (Adult)
1	<0.1	Negligible	0.00	0.00
2	≥ 0.1 and < 1	Low	2.94	17.65
3	≥ 1 and < 4	Moderate	29.41	35.29
4	≥ 4	High	67.65	47.06

infrastructure, and fragmented governance. Socio-economic barriers, such as community reliance on untreated groundwater and limited awareness of contamination risks, further impede progress. However, there are opportunities to integrate circular economy principles into water management practices. This study's findings can guide targeted water management by identifying contamination hotspots for focused remediation. Health risk data can support the design of public health interventions for vulnerable groups, and the results advocate for stricter industrial regulations to reduce pollution. Additionally, the findings endorse cost-effective, localized purification solutions tailored to specific regional contaminants. Implementing circular economy principles, such as recycling industrial wastewater or repurposing metal-laden sludge, could further minimize pollution at its source. This approach enhances resource efficiency and helps lessen the environmental impact of industrial activities.

Future research should focus on isotopic tracing to differentiate between industrial discharges and natural geological sources, which will enhance accountability. Implementing multi-seasonal sampling alongside advanced geospatial tools, such as machine learning-based mapping, will enhance both temporal and spatial accuracy. Additionally, broadening risk assessments to encompass dermal and inhalation pathways, as well as socio-economic data, can help create fair policies for marginalized communities. Pilot projects that explore biochar filtration or constructed wetlands, designed to suit local hydrology and industrial types, could improve remediation efforts. Policymakers need to enforce stricter discharge standards, support community-led initiatives, and encourage collaboration across sectors to ensure that industrial growth aligns with sustainable development goals.

4. Conclusion

This study comprehensively evaluated the heavy metal contamination in the groundwater of the Chittagong industrial area, highlighting significant risks to water security and public health. The findings revealed substantial contamination by heavy metals such as arsenic, cadmium, chromium, lead, manganese, and iron. The Heavy Metal

Table 6
Values of Carcinogenic Risk (CR) and Total Carcinogenic Risk (CRt) for children and adults through ingestion pathway (Edokpayi et al., 2018; USEPA, 2001).

Heavy metal	Cancer Risk (Child)				Cancer Risk (Adult)				CSF (mg Kg^{-1} day^{-1})
	Minimum	Maximum	Mean	Sample (%) surpass limit (USEPA, 2001).	Minimum	Maximum	Mean	Sample (%) surpass limit (USEPA, 2001).	
Cr	0.00	6.50E-03	1.89E-03	67.65	0.00	2.79E-03	7.05E-04	47.06	0.5
As	0.00	1.02E-02	2.04E-03	82.35	0.00	4.37E-03	6.70E-04	70.59	1.5
Cd	0.00	7.73E-03	2.95E-03	79.41	0.00	3.31E-03	1.17E-03	67.65	6.1
Pb	0.00	6.35E-05	2.71E-05	0.00	0.00	2.72E-05	9.03E-06	0.00	0.0085
∑ CR	4.53E-06	1.94E-02	6.91E-03	85.29	1.94E-06	8.30E-03	2.47E-03	76.47	

Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI) indicated that over 50 % of the samples were unsuitable for drinking. The spatial distribution maps highlighted significant variability, with the southern regions being the most affected due to their proximity to industrial zones. The health risk assessment revealed significant non-carcinogenic and carcinogenic threats. The Hazard Quotient (HQ) analysis indicated significant chronic health risks, primarily attributed to arsenic, lead, cadmium, and chromium exposure. Furthermore, the Hazard Index (HI) revealed that 67.65 % of adults and 47.06 % of children are at risk of chronic health effects due to prolonged exposure to these contaminants. Children faced higher chronic exposure risks than adults, driven by lower body weight and ingestion rates. The carcinogenic risk assessment revealed that both children and adults face significant carcinogenic risks, particularly from arsenic, cadmium, and chromium, with cancer risk values far beyond acceptable limits set by regulatory standards. To address these gaps, it is essential to prioritize site-specific solutions, such as employing ion exchange for arsenic removal and bioremediation for heavy metals removal. Also, cost-benefit analyses should be conducted to ensure these solutions can be scaled up. To protect vulnerable populations, policy measures like mandatory school water quality screening programs and subsidized household filtration systems (such as activated alumina filters) should be put in place to reduce exposure risks. This study is significant due to the widespread concern over groundwater contamination by heavy metals, which remains a critical environmental and public health issue in many industrial regions across the world.

CRediT authorship contribution statement

Md. Swadhin Hossain: Writing – review & editing, Writing – original draft, Visualization, Methodology, Formal analysis, Conceptualization. **Ashfaqur Rahman:** Investigation, Data curation, Conceptualization. **Elsai Mati Asefa:** Writing – review & editing, Methodology, Formal analysis. **Mahfuza Parveen:** Writing – review & editing, Supervision. **Md. Reaz Uddin:** Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data is available from the corresponding author upon reasonable request.

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